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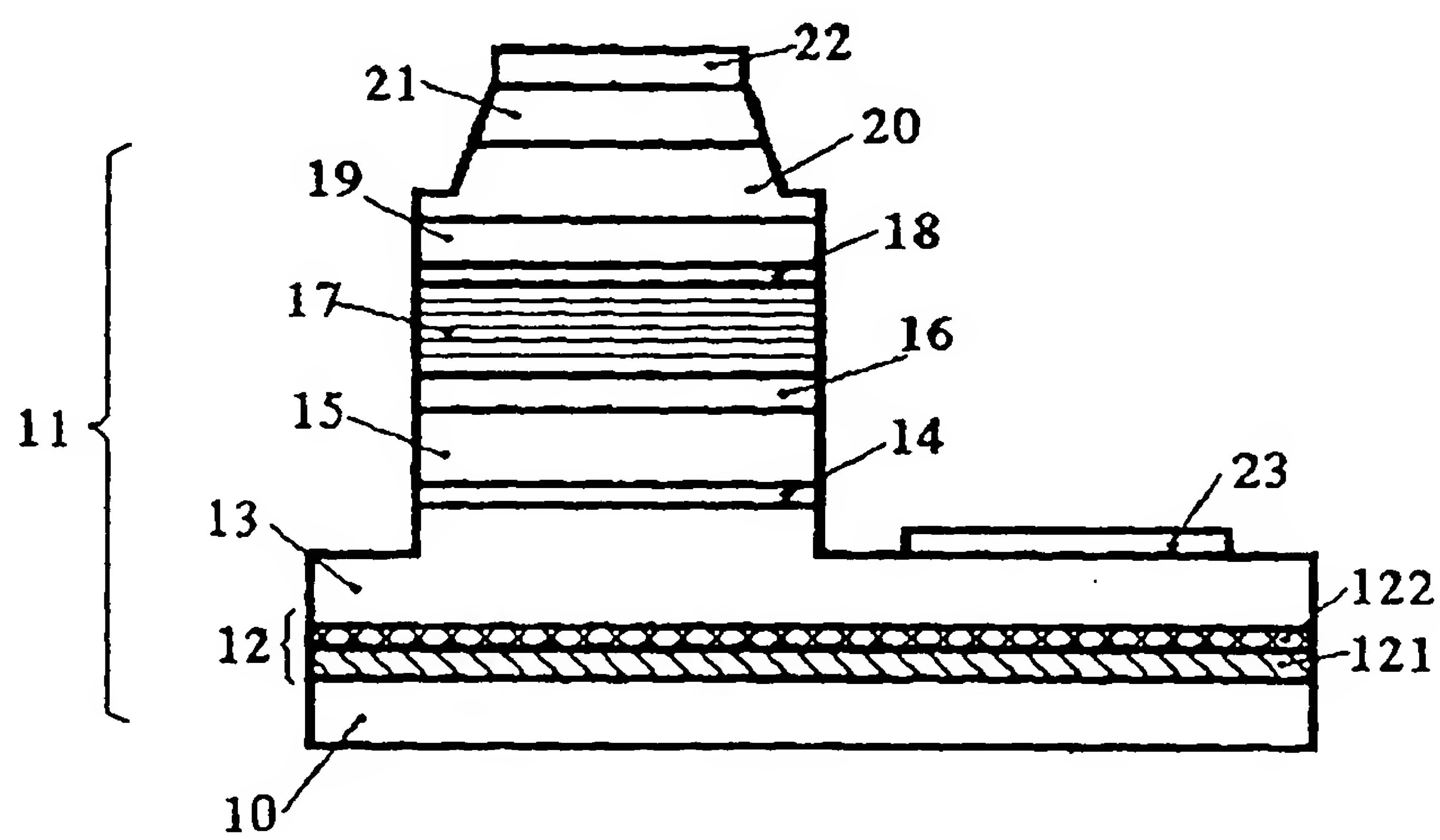

(57) Abstract

Semiconductor device based on heteroepitaxial films of nitride compounds Ga_{1-x}-Al_xN includes monocrystalline sapphire substrate, with the orientation of the working surface, containing directions <1100>, on which is located heteroepitaxial layered structure, consisting of at least one buffer sublayer and one layer of the semiconductor nitride compound $Ga_{1-x}Al_xN$, where: $0 \le x \le 1$. Buffer sublayer is made of the material, crystalline structure of which belongs to the cubic syngony with parameter "a" of the unit cell, lying within the limits from 1.05 n to 1.20 n (Å), where n = 3, 4, 6, 8, and at the same time surface of the sublayer contains direction <112>, parallel to the direction <1100> of the substrate surfaces and of the surfaces of the semiconductor films. Structures of the different semiconductor devices: heterolaser, light emitting diode, photo diode, and field effect transistors are shown.

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SEMICONDUCTOR DEVICE BASED ON HETEROEPITAXIAL FILMS OF NITRIDE COMPOUNDS $Ga_{1-x}Al_xN$

BACKGROUND OF THE INVENTION

1.Field of the Invention

The Invention belongs to the area of state electronics, namely to the semiconductor devices, designed for the amplification, generation, and switching of the electromagnetic oscillations, capable to work at extended levels of power and temperature, as well for the reception and generation of optical oscillations in the visible and ultraviolet wavelength ranges.

2. Prior Art

Perspective semiconductor devices based on the heteroepitaxial films of the nitride compounds of type $A^{III}B^{V}$ (e.g. H.Morkos et al, Large-band-gap SiC,III-V nitride and II-VI ZnSe-based semiconductor device technologies, *J.Applied Physics*, v.76, N 3; 1 August 1994, p.p. 1363-1398) [1]. The main disadvantage of such devices is the bad working parameters reproducibility, fast degradation of the films due to the high 10^8 - 10^{10} cm^{-2} defect concentration. These defects are due to high lattice parameters mismatch between the contacting lattice planes of the substrate and of the superconductor film. For currently used monocrystalline substrates, used for the heteroepitaxial growth of the (0001) GaN films, the mismatch is 16% for the (0001) Al_2O_3 , 9.5% for (111) $MgAl_2O_4$, 3.5% for (0001) SiC. To reduce the mismatch the buffer layer is used, located between the working surface of the substrate and semiconductor film. This buffer layer is made of the materials with wurtzite type crystal structure: ZnO, GaN, AlN.

Known is semiconductor device - light emitting diode, technology of which is described in (see, T.Detchprohm et al, Hydride vapour phase epitaxial growth of high quality GaN films using ZnO buffer layer., *Appl.Phys.Lett.*, v.61, N 22, p.p. 2688-2690, 1992) [2]. This device includes the sapphire substrate with the orientation of the working surface (0001) with the heteroepitaxail structure built on it.

The heteroepitaxial structure includes: *a)* buffer sublayer of zinc oxide 500 Å thick, designed to reduce the mismatch between the (0001) plane of the substrate and heteroepitaxial semiconductor films of nitride compounds $A^{III}B^{V}$, making the active region of the device; *b)* *n*-emitting film of GaN, doped with *n*-type conduction silicon with thickness of - 3 mkm; *c)* thin (thickness of 20 Å) active film of the undoped solid solution $In_{0.05}Ga_{0.95}N$; *d)* *p*-emitting film of GaN, doped by *p*-type magnesium, with thickness of 1 mkm. Part of the surface and emitter layers is covered by the ohmic contacts of Ti/Al for *n*-GaN and Ni/Au for *p*-GaN.

Analysis shows, that this structure does not provide high stability and reproducibility of the device characteristics.

Indeed, hexagonal plane parameters mismatch between the contacting planes (0001) ZnO and (0001) GaN is small: 2,3%. But unfortunately, mismatch for other planes in contact: (0001) ZnO and (0001) Al_2O_3 is 14%. Such large mismatch is due to the fact, that contacting planes (0001) Al_2O_3 and (0001) ZnO are twisted relative to each other by 30° around the [0001] direction, so that direction $<1\bar{1}00>$ of Al_2O_3 is parallel to $<11\bar{2}0>$ ZnO. Translation period along $<1\bar{1}00>$ Al_2O_3 equals 2,747 Å , and for $<11\bar{2}0>$ ZnO - 3,25 Å, which creates the large mismatch.

Due to the large mismatch the (0001) ZnO film can grow on (0001) Al_2O_3 only by "island" (three-dimensional) growth mechanism. This growth mechanism, as known, allows to obtain only the "mosaic'" crystal structure film, consisting of separate grains with large amount of grain boundaries and high structure defect concentration. Naturally, the thin semiconductor films, grown on such buffer film, also have the "mosaic" crystal structure with large amount of grain boundaries and high defect concentration

As (0001) Al_2O_3 and (0001) GaN are twisted relative to each other by 30° around the direction [0001], and cleavage planes of Al_2O_3 and GaN are also twisted around direction [0001] by the same angle of 30°. This creates severe technological difficulties in manufacturing semiconductor laser with mirrors made on the cleavage planes of the semiconductor films.

SUMMARY OF THE INVENTION

The goal of the invention is to develop semiconductor device based on heteroepitaxial films of nitride compounds $Ga_{1-x}Al_xN$, with better working parameters stability and enhanced lifetime.

Semiconductor device includes:

monocrystalline sapphire substrate, with the working surface, containing at least one of $\langle 1\bar{1}00\rangle$ directions,

heteroepitaxial layer structure, made on the working surface, and containing, at least, one buffer sublayer and at least one layer of semiconductor nitride compound $Ga_{1-x}Al_xN$, where: $0\leq x \leq 1$, and at least two electrodes,

the said buffer sublayer is located between the working surface of the substrate and the said layer of semiconductor nitride compound $Ga_{1-x}Al_xN$.

Semiconductor device differs by buffer sublayer made of material, crystalline structure of which belongs to the cubic syngony, and parameter "a" of the unit cubic cell is chosen according to the condition:

$$1{,}05\, n \leq a\ (\text{Å}) \leq 1{,}20\, n\ , \text{ where } n = 3,4,6,8 \qquad (1),$$

at the same time this direction $\langle 1\bar{1}00\rangle$, located in the working surface of the substrate parallel to direction $\langle 112\rangle$, located in the surface and the aforementioned buffer sublayer.

Buffer sublayer made of material with crystalline structure of α-Fe type, with parameter "a" of it's unit cell from the range from 3,15 Å to 3,60 Å.

Besides, buffer sublayer can be made of material with crystalline structure of NaCl type and with the unit cell parameter "a" within the range of values from 4,20 Å to 4,80 Å.

Buffer sublayer may be also made of material with crystalline structure of spinel type and with unit cell parameter "a" within the range from 8,40 Å to 9,60 Å.

In addition to that, buffer sublayer can be made of material, with conductivity large enough to perform the function of the electrode.

The result is achieved based on the following arguments.

As known, the polytypism is characteristic for the gallium and aluminum nitrides. They can crystallize both in hexagonal and cubic modifications. Hexagonal GaN and AlN

have wurtzite structure, while their cubic modifications have structure of zinc blende type. The two modifications differ only by the sequence of the densely packed planes, and hexagonal unit cell parameters are closely related to the parameters of its cubic polytype unit cell. For the same compound $a_{hexagonal} = 1/2 \cdot \sqrt{2}\ a_{cubic}$. As the densely packed planes (0001) and (111) of the polytypes of the same compound have the same symmetry and plane mesh parameters, we can consider only the case when the heteroepitaxial film with the wurtzite structure, for instance, is deposited on the heteroepitaxial buffer sublayer with cubic structure.

As we have noticed before, large lattice parameters mismatch between the Al_2O_3 (0001) and (0001) of wurtzite, for instance GaN, is due to the 30° twist around the [0001] direction. We noticed that once the twist is eliminated, the lattice parameters mismatch becomes substantially smaller. Indeed, two translations periods along $<1\bar{1}00>$ of Al_2O_3 ($2 \cdot 2.747 = 5.494$ Å) coincides with the 0.5% accuracy with the a single translation along $<1\bar{1}00>$ GaN, equal 5.52Å, two translations along $<11\bar{2}0>$ Al_2O_3, equal $2 \cdot 4.76 = 9.52$ Å, is also with the 0.5% accuracy coincides with three translations along $<11\bar{2}0>$ GaN ($3 \cdot 3.189 = 9.56$ Å).

To eliminate the twist, we propose to use a buffer (intermediate) layer (or several layers) of the material with cubic syngony, which at the heteroepitaxy on (0001) Al_2O_3 has the surface orientation {111}, and direction <112> in this plane is parallel to the $<1\bar{1}00>$ type direction of the Al_2O_3, lying in the (0001) plane of Al_2O_3. When the wurtzite type material is further grown on the {111} surface of the cubic syngony material, the following epitaxial relationships can be obtained:

$$(0001)\ Al_2O_3 \parallel \{111\}_{cubic} \parallel (0001)_{wurtzite} \quad (2),$$

$$<1\bar{1}00>\ Al_2O_3 \parallel <112>_{cubic} \parallel <1\bar{1}00>_{wurtzite} \quad (3).$$

In this case the lattice parameters mismatch between the sapphire substrate surface and semiconductor film is practically absent.

Besides, cleavage planes of sapphire and wurtzite, become parallel. This makes cleavage planes of the sapphire substrate and of the semiconductor film with wurtzite structure, forming the active region of the semiconductor device -- heterolaser, being paral-

lel. This is especially important for the laser device fabrication.

Therefore, almost perfect lattice parameters match between, for instance, (0001) Al_2O_3 and {111} of the buffer layer on one side, and {111} of the buffer sublayer and (0001) of the film with wurtzite structure, for instance, GaN , on the other side, can be achieved. Then the cubic lattice unit cell parameter of the buffer sublayer material a can be determined from the relationship:

$$a \cdot \sqrt{2} \cdot \sqrt{3} = n \cdot 2.747\ (\text{Å}), \qquad (4)$$

where 2.747Å - is a translation period along Al_2O_3 <$1\bar{1}00$>, and n is an integer, which gives: $a = 1.125\ n$ Å .

As the unit cell lattice parameters of the Ga, In and Al nitrides, as well as solid solutions of Ga, In, and Al, used in semiconductor devices, are within the range from 3.11 to 3.25 Å . Materials with a unit cell parameter a less than 2.5 Å , or greater, than 13Å are practically absent. According to the Invention, it is reasonable to use as buffer sublayer materials with cubic syngony with the value of a within the range of $1.05\ n$ to $1.20\ n$ Å, where n equals 3, 4, 6, 8. Values of 5, 7, 9 or 10 are not acceptable for n . , these values do not allow to achieve the desired result.

Note, that in case when the deposited heteroepitaxial semiconductor film with the polytype structure of zinc blende type, heteroepitaxial buffer layer material is also chosen according to the aforementioned conditions.

Thus, Invention allows:

a) to improve structure perfection of the heteroepitaxial nitride films of compound of type $A^{III}B^{V}$, forming active region of the semiconductor device, and, hence, to substantially improve the device characteristics reproducibility and to enhance it's lifetime;

b) to eliminate 30^0 twist of the cleavage planes of sapphire substrate and semiconductor films. This allows to manufacture laser resonator cavity of the cleavage plane of semiconductor films.

Heteroepitaxial buffer sublayer may be made of the material with cubic syngony with crystalline lattice of different types, like for instance α-Fe, NaCl, spinel. Buffer sublayer materials can be dielectrics, like for instance $BaCeO_3$, MgO, In_2CdO_4 or

Na_2MoO_4, or conducting materials, like for instance nitride and carbide of niobium, hafnium, scandium, titanium, their solid solutions, as well as metals: niobium, tantalum.

Buffer sublayer, made of conducting material, can in addition play a role of one of the electrodes of the device.

Heteroepitaxial layered structure may contain several buffer sublayers. Using several buffer sublayers significantly broadens the possibilities of more gradual matching of the crystal lattices parameters and thermal coefficients of sapphire substrate and buffer sublayer, on one side, and buffer sublayer and semiconductor nitride film, on the other. But, according to this Invention, when several buffer sublayers are used at least one of them, must made of the material with cubic syngony and with parameter a, satisfying the condition (1). For instance, layered structure may contain buffer sublayers of niobium and it's nitride, or one sublayer of niobium, and another sublayer - of hafnium nitride, or one sublayer of hafnium nitride, and another - of zinc oxide,- material with wurtzite structure.

Sapphire substrate can have orientations with it's working surface not only (0001), but also other orientation, that contains direction of <$1\bar{1}00$> type. These surfaces, are twisted from the basal surface and (0001) around direction <$1\bar{1}00$> by an angle, the value of which is in the range from 0° to 90°. Example of such surface are planes of type {$11\bar{2}0$}, on which, as on (0001) Al_2O_3, may be grown: heteroepitaxial buffer sublayer of the material with cubic syngony with orientation of the surface {111} and heteroepitaxial semiconductor film of compound $Ga_{1-x}Al_xN$ with wurtzite structure, with orientation (0001), and/or their zinc blende polytypes with orientation {111}, and one of the directions of <112> type of the surface of sublayer being parallel to <$1\bar{1}00$>-type direction of the surface of the substrate and wurtzite films, or, correspondingly, <112> of films with zinc blende structure. This can be surfaces of type {$11\bar{2}l$}, where l - real number. On these surfaces may be grown heteroepitaxial sublayer of material with cubic syngony, with at least one of the directions of type <112> of it's surface being parallel to direction of type <$1\bar{1}00$> of the surfaces of substrate and films.

For the semiconductor device fabrication, for instance, such as heterolasers, light emitting diodes, field effect transistors, that have active region consisting of the multilayer semiconductor heterostructure with "quantum dots", "quantum wires", the substrates with

non-singular (low-symmetry), in particular "vicinal" working surfaces are used. Such surfaces are not atomically smooth, and can be represented as multi-step surfaces, bound by the low Miller index planes. It is possible, under certain conditions, to obtain "quantum dots", and "quantum wires" on such surfaces, as a result of the self-organisation growth process.

According to the Invention, it is possible to use sapphire substrates with the working non-singular surface, containing direction $\langle 1\bar{1}00 \rangle$, which also belongs to the $\{11\bar{2}l\}$ family. Buffer sublayer surface, grown on such working surfaces of the sapphire substrate, is also a non-singular plane. It belongs to the family of planes containing direction of type $\langle 112 \rangle$. Direction $\langle 112 \rangle$, located in the surface of the sublayer, is parallel to the $\langle 1\bar{1}00 \rangle$ direction of the substrate working surface. And the surface of the semiconductor film, deposited on the non-singular buffer sublayer surface, belongs to the $\{11\bar{2}l\}$ family and their $\langle 1\bar{1}00 \rangle$ direction is parallel to $\langle 112 \rangle$, located in the surface of the sublayer.

BRIEF DESCRIPTION OF THE DRAWINGS

Figures show structures of some of the types of the semiconductor devices, that can be realized according to this invention:

FIG.1 - heterolaser;

FIG.2 - light emitting diode;

FIG.3 - photo diode for the ultraviolet wavelength range;

FIG.4 - field effect transistor (FET);

FIG.5 - field effect transistor (FET);

FIG.6 - high electron mobility field effect transistor (HEMT).

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Example 1. FIG.1 shows structure of the semiconductor device - heterolaser - multi-quantum-well (MQW) structure laser diode (LD) of the blue wavelength range.

Laser contains sapphire substrate 10 with orientation of working surface (0001), containing direction $\langle 1\bar{1}00 \rangle$. On the substrate **10** is located heteroepitaxial layered struc-

ture **11**, with the buffer sublayer **12**. According to condition (1) buffer sublayer **12** with thickness of 500 Å is made of niobium (Nb), material with cubic syngony, with crystalline structure of α-Fe type, with unit cell parameter a = 3,30 Å. Sublayer has orientation $\{111\}$, with the direction $\langle 112 \rangle$ of the surface $\{111\}$ of Nb being parallel to the directions $\langle 1\bar{1}00 \rangle$ of the (0001) surface of the substrate **10** and semiconductor films (layers **13-21**).

Structure contains layer **13** of GaN (thickness 3 mkm), *n*-type conduction, doped with Si; layer **14** of the $In_{0.05}Ga_{0.95}N$ compound, thickness 0,1 mkm, *n*-type, doped by Si, and also a layer **15** of the compound $Al_{0.08}Ga_{0.92}N$ (thickness 0,5 mkm), *n*-type, doped by Si. Further are located: layer **16** - of GaN (0,1 mkm thick), *n*-type, doped by Si, **17** - laser active region, consisted of the heterostructure of $In_{0.15}Ga_{0.85}N$ - $In_{0.02}Ga_{0.98}N$ with three "quantum wells". This heterostructure contains three films of $In_{0.15}Ga_{0.85}N$, doped by Si, with thickness 35 Å each, that make quantum wells. Between these films are located two wider-gap films of $In_{0.02}Ga_{0.98}N$, doped by Si, each having thickness of 70 Å. Then goes the layer **18** of the compound $Al_{0.2}Ga_{0.8}N$, doped by Mg, *p*-type, with thickness of 200 Å, layer **19** of *p*-GaN, doped by Mg, thickness 0,1 mkm. Then follows the layer **20** of compound $Al_{0.08}Ga_{0.92}N$, doped by Mg, *p*-type (thickness 0,5 mkm), and a layer **21** of GaN, doped by Mg, *p*-type (thickness 0,3 mkm). Position **22** is an electrode of Ni/Au providing an ohmic contact to *p*-GaN, and pos. **23** - electrode Ti/Al providing the ohmic contact to *n*-GaN.

Layers **16** and **19** serve as optic waveguides, and layers **15** and **20** are the emitting layers. When constant voltage is applied to the electrodes **22** and **23** in the forward direction, the non-equilibrium charge carriers are injected from emitting films **15** and **20** into the laser active region **17**, recombination of which generates blue light radiation.

Heterolaser contains the Fabri-Perot resonator (not shown at figure), formed by the mirrors of the cleavage planes of the heteroepitaxial semiconductor films. These mirrors are covered by the λ/4 dielectric layers of TiO_2 - SiO_2. Layers **13, 14** and **21** are auxiliary. They provide more homogeneous current density, reduce internal mechanical stresses, reduce concentration of the defects and other recombination centers on the boundaries of the heterojunctions of the laser active region.

Example 2. Structure of the semiconductor device - heterolaser is analogous to the *example 1* (see. FIG.1).

Sapphire substrate **10** has orientation of the working surface $(11\bar{2}0)$, containing directions of type $<1\bar{1}00>$, on which the buffer sublayer **12** with thickness 100 Å of hafnium nitride (HfN) (structure of the NaCl type, parameter a = 4,50 Å) is deposited. Sublayer **12** has orientation {111} HfN, with one of the direction <112> HfN parallel to the direction of type $<1\bar{1}00>$, located in the planes $(11\bar{2}0)$ of the substrate **10** and (0001) of the semiconductor films (layers **13 - 21**).

Example 3. Structure of the semiconductor device - heterolaser is similar to the *example 1* (see. FIG.1).

Heteroepitaxial layered structure **11** contains two buffer sublayers **12**: first **121**, located on the surface of the substrate **10**, made of Nb (parameters see above) and on top of it is deposited the second sublayer - **122** of niobium nitride NbN (structure of the NaCl type, a = 4,40 Å). Both sublayers have orientation {111} and <112> Nb and <112> NbN are parallel to the $<1\bar{1}00>$ of the substrate **10** and semiconductor films (layers **13-21**).

Example 4. Structure of the semiconductor device - heterolaser similar to the *example 2* (see. FIG.1).

Heteroepitaxial layered structure **11** contains two buffer sublayers **12**: the first sublayer -**121**, thickness 100 Å , made of HfN (see parameters above) is located immediately on the substrate 10 surface, and the second sublayer - **122** of zinc oxide ZnO (thickness 0,5 mkm) is deposited on top of it. Orientation of this sublayer **121** is - {111} HfN, and sublayer **122** (0001) ZnO and with <112> HfN and $<1\bar{1}00>$ ZnO parallel to the $<1\bar{1}00>$ of the substrate 10 and semiconductor films (layers **13-21**).

Example 5. Structure of the semiconductor device - heterolaser similar to *example 1* (see. FIG.1).

Substrate **10** has orientation of it's surface $\{11\bar{2}6\}$, containing direction $<1\bar{1}00>$. Buffer sublayer **12** is made of HfN (parameters see above) with thickness 1000 Å . Located at the surface of sublayer **12** direction <112> HfN is parallel to $<1\bar{1}00>$ surface of the substrate 10.

Example 6. Structure of the semiconductor device - heterolaser similar to *example 1* (see. FIG.1).

Substrate **10** of Al_2O_3 has as it's working surface - non-singular "vicinal" surface $\{11\bar{2}0\}$, containing direction <1$\bar{1}$00>. Surface of the buffer sublayer **12** of Nb (with parameters as above) is also a non-singular plane, containing <112> of Nb parallel to the <1$\bar{1}$00> surface of the substrate **10**. Surfaces of the layers **13 - 21** are also characterised non-singular plane belonging to the family $\{11\bar{2}l\}$, which <1$\bar{1}$00> is parallel to the <112> of Nb. Active region of the laser is a heterostructure of the solid solution $In_{0,15}Ga_{0.85}N$ - $In_{0.02}Ga_{0.98}N$ with "quantum dots".

Example 7. Structure of the semiconductor device - heterolaser similar to the *example 1* (see. FIG.1).

Buffer sublayer **12** (thickness 500 Å) of bohr phosphide (BP) (structure of the sphalerite type with a = 4,53 Å). Orientation of the sublayer **12** {111} BP. At the same time <112> of BP is parallel to the <1$\bar{1}$00> of the substrate **10.**

Example 8. Structure of the semiconductor device - heterolaser similar to the *example 1* (see. FIG.1).

Buffer sublayer **12** (thickness 800 Å) made of compound In_2CdO_4 (structure of the spinel type, a = 9,11 Å). Orientation of the sublayer 12 - {111} In_2CdO_4 . At the same time direction <112> of the In_2CdO_4 is parallel to the <1$\bar{1}$00> of substrate **10** and semiconductor layers **13-21**.

Example 9. Structure of the semiconductor device -heterolaser similar to the *example 1* (see. FIG.1).

Buffer sublayer **12** (thickness 800 Å) made of the solid solution $In_{0.7}Ga_{0.3}CdO_4$ (structure of the spinel type, a = 8,98 Å). Orientation of the sublayer **12** is - {111}. At the same time direction <112> of $In_{0.7}Ga_{0.3}CdO_4$ is parallel to the <1$\bar{1}$00> of the substrate **10** and semiconductor layers **13-21.**

Example 10. FIG.2 presents structure of the semiconductor device - light emitting diode.

The light emitting diode contains sapphire substrate **30** with orientation (0001), containing directions <1$\bar{1}$00> On the substrate **30** is located heteroepitaxial layered struc-

ture **31**. It includes two buffer sublayers: **321** and **322**, made of, correspondingly, tantalum (Ta) (structure of the α-Fe type; a = 3,30 Å), thickness of 50 Å , and it's carbide (TaC) (structure of the NaCl type with a = 4,45 Å), and thickness 800 Å . Sublayers **321** and **322** have orientation {111} and their directions $<112>$ Ta and $<112>$ TaC are parallel to the $<1\bar{1}00>$ of the surface (0001) of the substrate **30** and semiconductor films (layers **34-38**). On the sublayer **322** is located layer **34** of AlN (thickness 1 mkm). Then follow: layer **35** of the n-GaN film (thickness 2 mkm); layer **36** - of the undoped compound $In_{0.45}Ga_{0.55}N$ (thickness 30 Å), layer **37** - of compound $Al_{0,2}Ga_{0.8}N$ p-type (thickness 0,1 mkm), layer **38** - p-GaN (thickness 0,5 mkm). Active region of the light emitting is formed by the three-layered (double) heterostructure (layers **35,36,37**) with one "quantum well". Electrode **39** of Ti/Al is located on the surface of the p-GaN layer **38**, and an electrode **40** of Ni/Au - on the part of the surface of the n-GaN layer **35**. When voltage is applied to the electrodes **39** and **40** in forward direction in the active region of the light emitting diode green light (with the wavelength 0,5 - 0,55 mkm) is generated.

__Example 11__. Structure of the semiconductor device - light-emitting diode similar to *example 10* (see. FIG.2).

Working surface of the sapphire substrate 30 with the orientation $\{11\bar{2}0\}$, contains directions $<1\bar{1}00>$. Buffer sublayer **32** is made of a single layer of NbN (parameters as above) of the {111} NbN orientation. At the same time direction $<112>$ of NbN is parallel to the $<1\bar{1}00>$ of the surface $\{11\bar{2}0\}$ of the substrate **30** and (0001) of the semiconductor layers **34-38**.

__Example 12__. Structure of the semiconductor device - light-emitting diode similar to *example 11* (see. FIG.2).

Heteroepitaxial structure **31** contains barrier sublayer **32** of the solid solution $Nb_{0.9}Hf_{0.1}N$ (structure of the NaCl type, a =4,41 Å), thickness of 500 Å . Orientation of the sublayer - is {111} $Nb_{0.9}Hf_{0.1}N$, and - $<112>$ $Nb_{0.9}Hf_{0.1}N$ is parallel to the $<1\bar{1}00>$ of the surfaces $\{11\bar{2}0\}$ of the substrate 30 and (0001) of the layers **34 -38**.

__Example 13__ . FIG.3 shows the structure of the semiconductor device - photo diode for the ultraviolet wavelength range.

Photo diode contains sapphire substrate **50** with orientation (0001), containing directions $<1\bar{1}00>$. On substrate **50** is located the heteroepitaxial layered structure **51**. It includes two barrier sublayers : **52** and **53**, made of, correspondingly, Nb (parameters as above) and titanium nitride (TiN) (structure of the NaCl type, a = 4,23 Å). Thickness of the sublayer **52** is 0,1 mkm, and thickness of the sublayer **53** is 0,5 mkm. Orientation of the sublayer **52** is - {111} Nb, of the sublayer **52** is - {111} TiN and their directions <112> Nb and <112> TiN are parallel to the directions $<1\bar{1}00>$ of the surfaces (0001) of the substrate **50** and of the semiconductor layers **54** and **55**. On the sublayer **53** are located: layer **54** of n-GaN (thickness 0,1 mkm) and layer **55** of p-GaN (thickness 0,1 mkm). On part of the surface of the layer **55**, ohmic contact **56** of Ni/Au is formed. Barrier sublayer **52** of conducting material - niobium does in addition serve as an electrode and is equipped with the contact **57** made of aluminum.

Example 14. . FIG.4 shows structure of the semiconductor device - field effect transistor (FET).

FET contains sapphire substrate **60** with orientation (0001), including directions $<1\bar{1}00>$. On this surface is located the heteroepitaxial layered structure **61**, consisted of buffer sublayer **62** (thickness 500 Å), made of Nb (parameters as above), with orientation {111}. At the same time directions <112> of Nb are parallel to the $<1\bar{1}00>$ of the substrate **60** and of the GaN layer **63**, doped by Si to concentration n = 10^{17} $cm.^{-3}$, with the electron mobility $\mu = 350\ cm^2.v^{-1}.s^{-1}$. Thickness of the layer **63** is - 0,6 mkm. On parts of the surface of the layer **63** are deposited films of Ti (thickness 25 Å) and Au (thickness 1500 Å), forming two ohmic contacts (electrodes) **64** and **65**: source (pos. **64**) and drain (pos. **65**). Between them is located the third electrode **66** of Ag - gate, that forms a Shottki barrier.

Example 15 . FIG.5 shows structure of the semiconductor device -FET of different design, than in *Example 14*.

FET includes sapphire substrate **70**. with orientation (0001). On the substrate **70** is located heteroepitaxial layered structure **71**. It contains buffer sublayer **72** (thickness 0,2 mkm) made of Nb (parameters as above), with orientation {111} Nb and buffer sublayer **73** (thickness 0.1 mkm) of HfN (parameters as above), with orientation

{111} HfN. At the same time directions <112> of Nb and <112> of HfN are parallel to $\langle 1\bar{1}00\rangle$ of the surfaces (0001) of the substrate **70**, and layer **74** of *n*-GaN, 0,3 mkm thick. On parts of the surfaces of the layer **74** are located two layers **75**, **76**, serving as source - layer **75** and drain - layer **76**, made of Ti (thickness 25 Å) and of Au (thickness 1500 Å). The gate of this transistor is a Shottki-barrier, formed of materials Nb and HfN of the buffer sublayers **72** and **73**. Connecting to the gate is made through the electrode **77**, made of aluminum film (thickness 0,2 mkm), and niobium sublayer **72**.

Example 16. .FIG.6 shows structure of the semiconductor device - high electron mobility field effect transistor (HEMT).

. Transistor contains sapphire substrate **80** with orientation (0001), on which is formed heteroepitaxial layered structure **81**. It contains the first buffer sublayer **82** (thickness 400 Å) of Nb (parameters as above), with orientation {111} and the second buffer sublayer **83** of HfN (parameters as above) (thickness a 3000 Å) with orientation {111}. Directions <112> of Nb and <112> of HfN are parallel to the $\langle 1\bar{1}00\rangle$ of the substrate **80** and of the semiconductor layer **84** of *n*-GaN (thickness 0,3 mkm). On the parts of the surface and this layer **84** are located two ohmic contacts - electrodes **85** and **86** of films of Ti (thickness 25 Å) and of Au (thickness 1500 Å), forming source and drain, correspondingly. On the layer **84** between the electrodes **85** and **86** is located layer **87** of $Al_{0.14}Ga_{0.86}N$ (thickness 0,1 mkm). On part of the surface of layer **87** is located the third electrode **88** of the transistor, forming Shottki barrier. Electrode **88** is formed by metallic film of the TiW alloy. This transistor exploits properties of the two-dimensional electron gas, formed on the boundary of the semiconductor heterostructure *n*-GaN – $Al_{0.14}Ga_{0.86}N$.

INDUSTRY APPLICABLE

Technical and economical advantages of this Invention are based on the enhanced lifetime of the semiconductor device, enhanced stability and reproducibility of the working parameters in mass production, due to the significant improvement of the crystal lattice perfection of the heteroepitaxial semiconductor films, forming active layers of the device. The Invention can be realized with current microelectronics technology.

CLAIMS

1. Semiconductor device based on heteroepitaxial films of nitride compounds $Ga_{1-x}Al_xN$, including:

monocrystalline sapphire substrate *(a)*, which has working surface *(b)*, containing at least one of directions <$1\bar{1}00$>,

heteroepitaxial layered structure *(c)*, formed on the working surface *(b)* and consisted of, at least, one buffer sublayer *(d)* and of at least one layer of *(e)* semiconductor nitride compound $Ga_{1-x}Al_xN$, where: $0 \le x \le 1$, and at least two electrodes *(f)*,

said buffer sublayer *(d)* is located between the substrate working surface *(b)* and said layer *(e)* of semiconductor nitride compound $Ga_{1-x}Al_xN$;

wherein:

said buffer sublayer *(d)* is made of material *(g)*, which crystalline structure has cubic syngony, with the parameter *"a"* of the unit cubic cell chosen according to the condition:

$1{,}05\, n \le a\,(\text{Å}) \le 1{,}20\, n$, where $n = 3, 4, 6, 8$,

at the same time direction <$1\bar{1}00$>, of the working surface *(b)* of the substrate is parallel to direction <112>, located in the surface of the said buffer sublayer *(d)*.

2. Semiconductor device according to claim 1, wherein said buffer sublayer *(d)* made of material *(g)* with crystalline structure of α-Fe type, with parameter *"a"* of it's unit cell in the range of values from 3,15 Å to 3,60 Å .

3. Semiconductor device according to claim 1, wherein according said buffer sublayer *(d)* made of the material *(g)* with crystalline structure of NaCl type, with parameter *"a"* of the unit cell in the range of values from 4,20 Å to 4,80 Å .

4. Semiconductor device according to claim 1, wherein said buffer sublayer *(d)* made of the material *(g)* with crystalline structure of spinel type, with unit cell parameter *"a"* in the range of values from 8,40 Å to 9,60 Å .

5. Semiconductor device according to any one of Claims 1 to 3 , wherein at least one of the said buffer sublayers *(d)* is made of the material *(g)* with conductivity enough to be used as an electrode *(f)*.

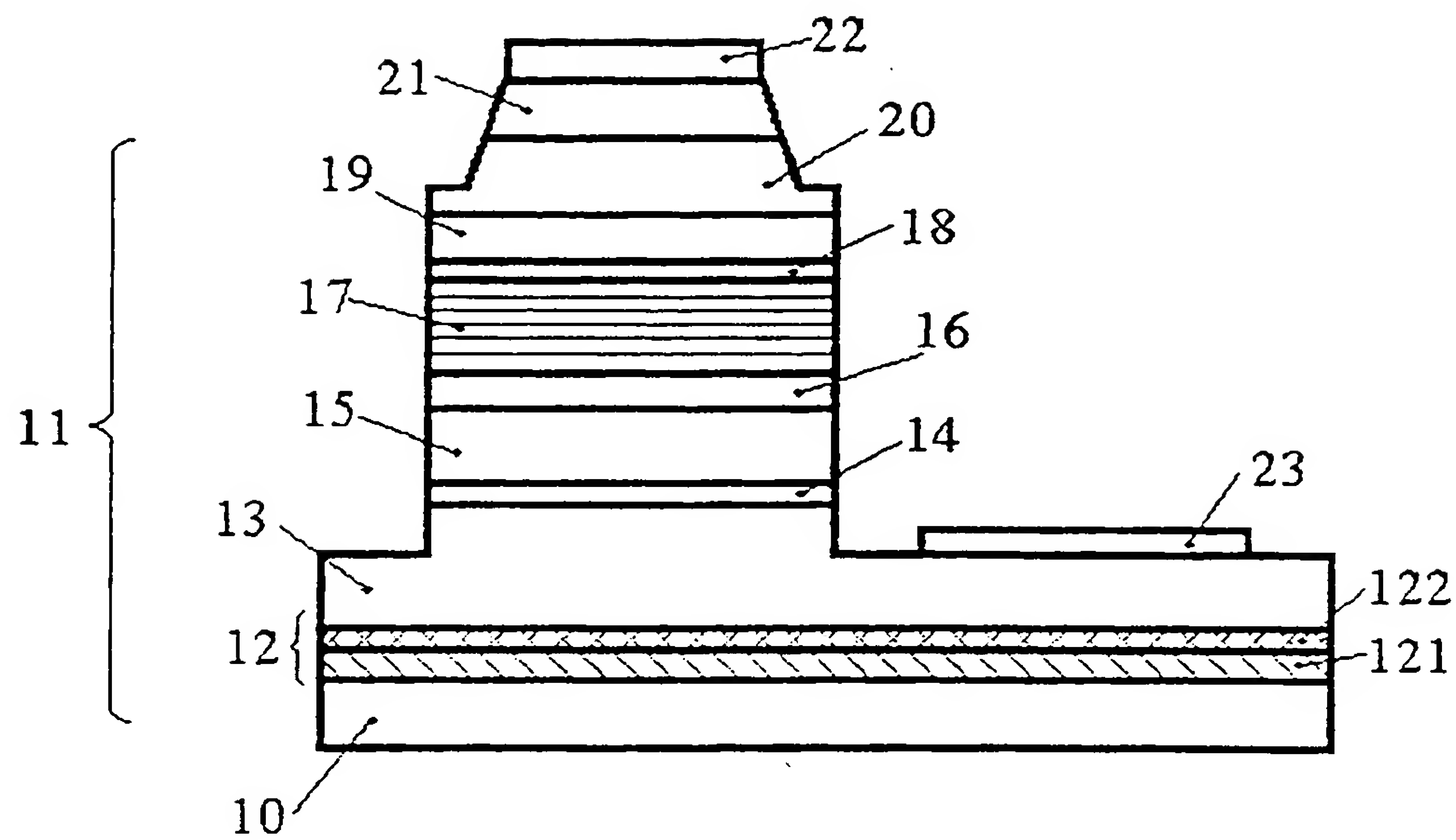
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FIG.1

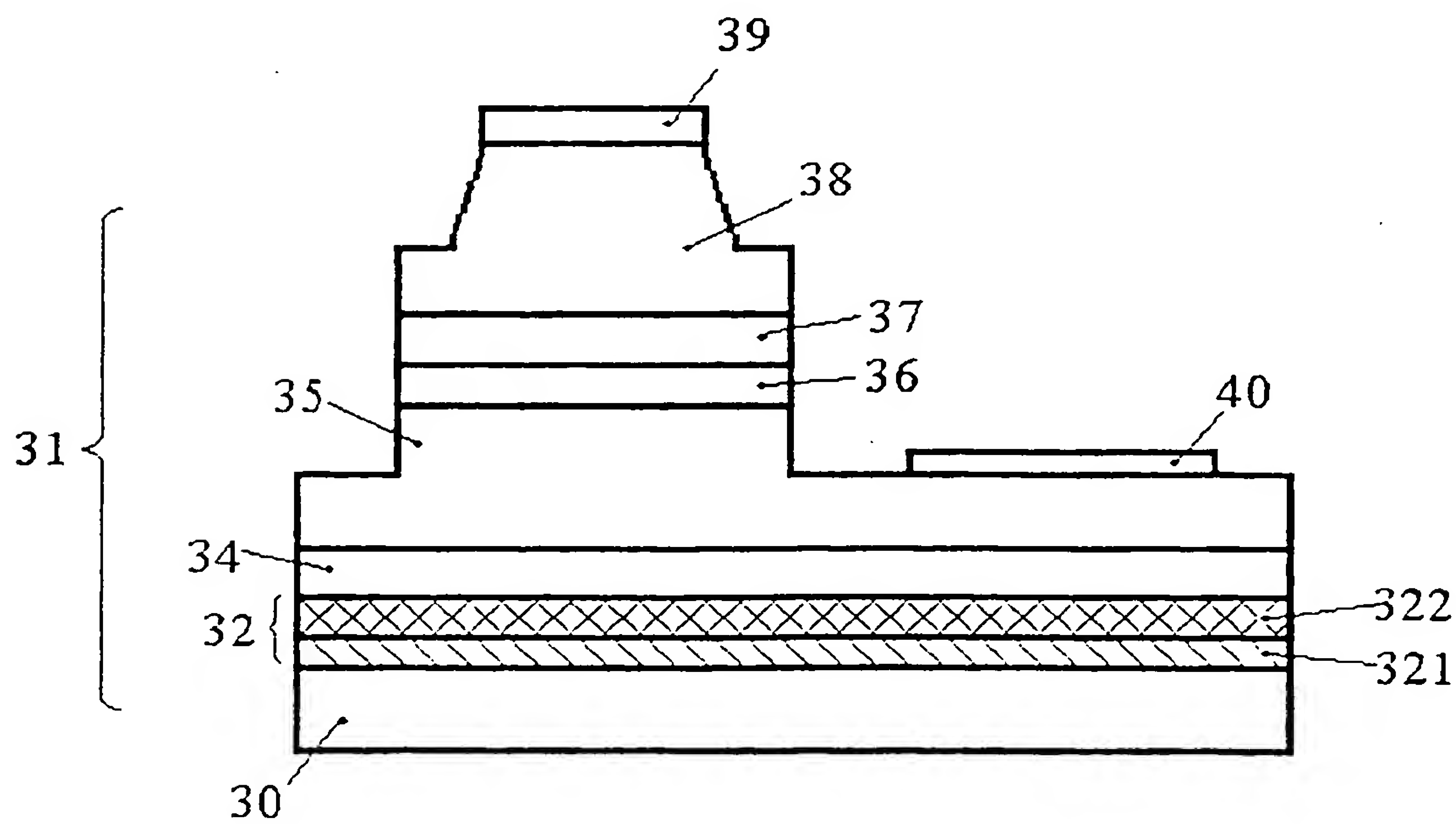
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FIG.2

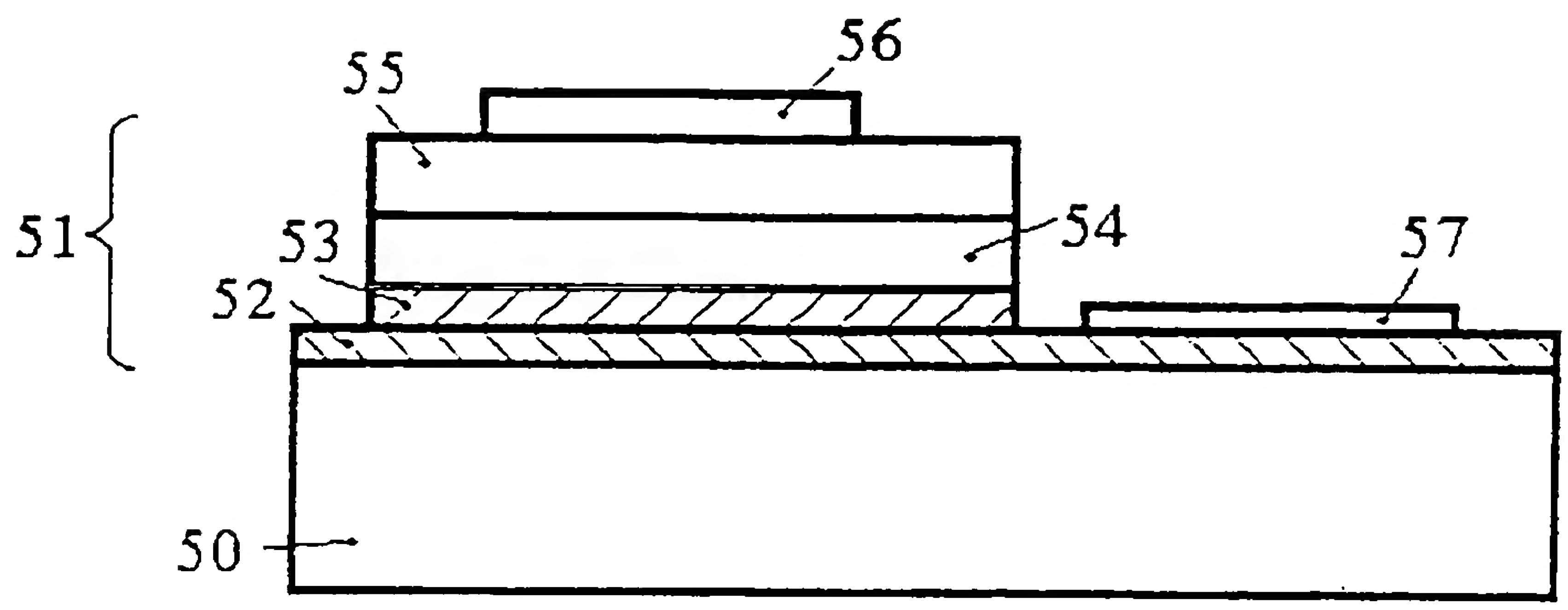

FIG.3

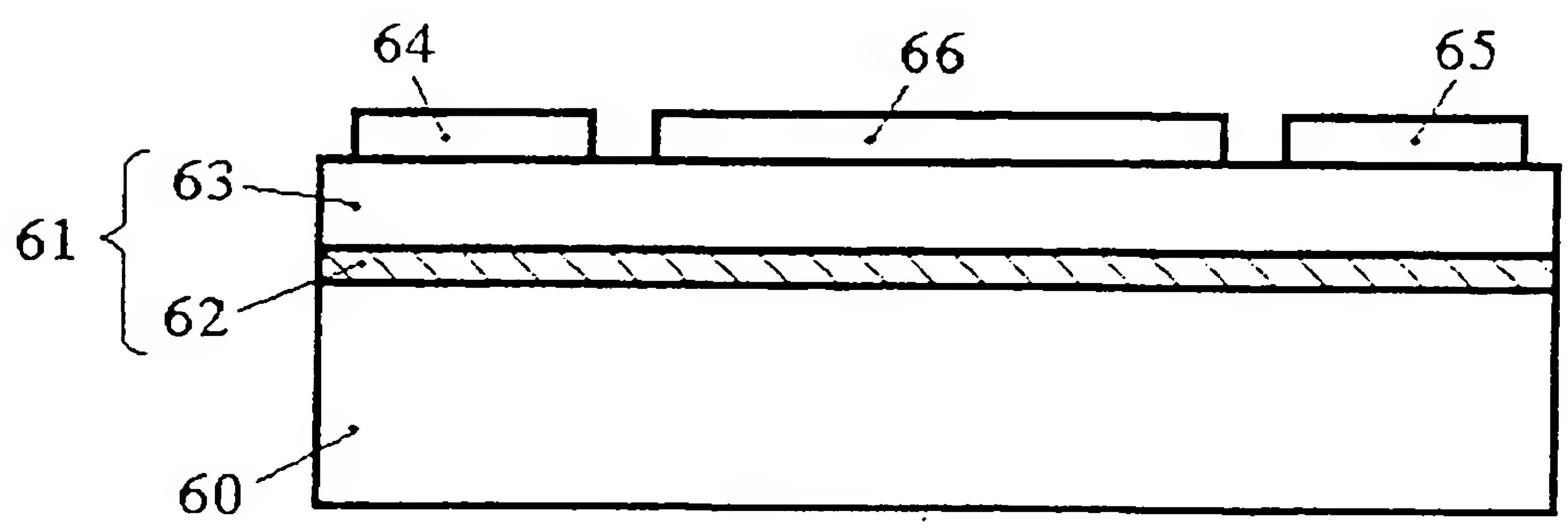

FIG.4

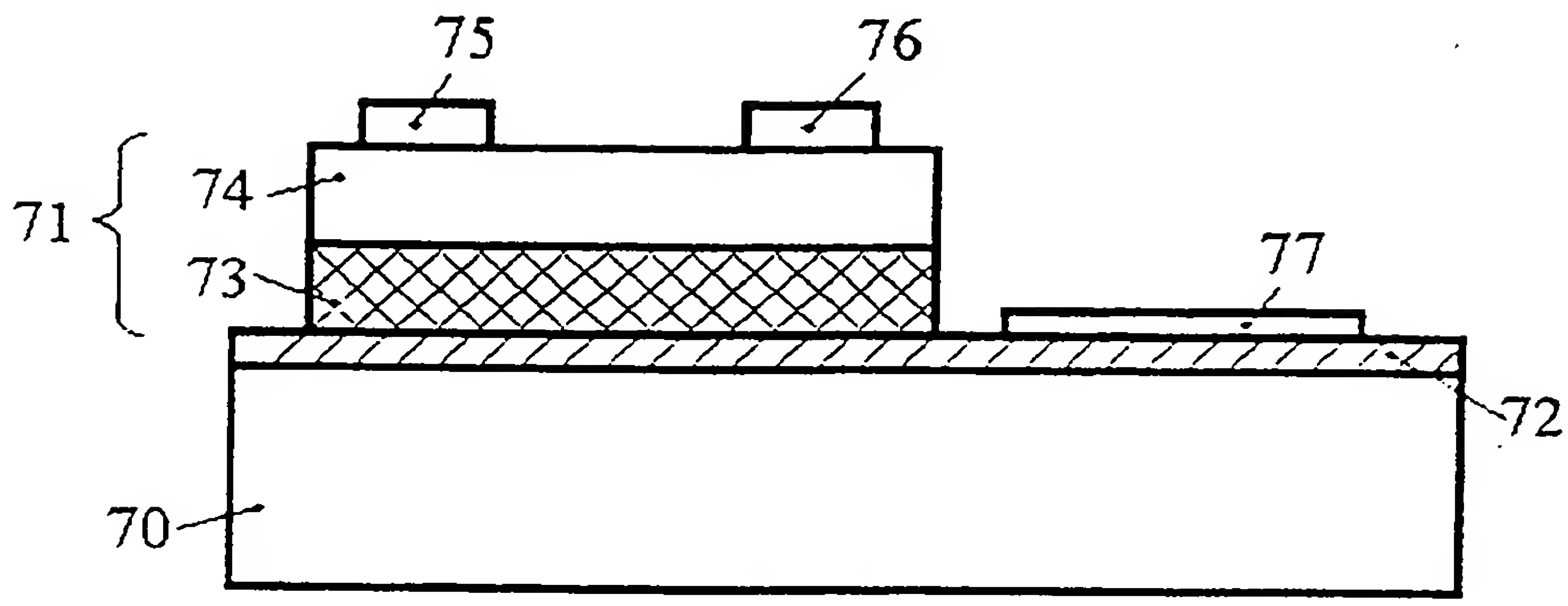

FIG.5

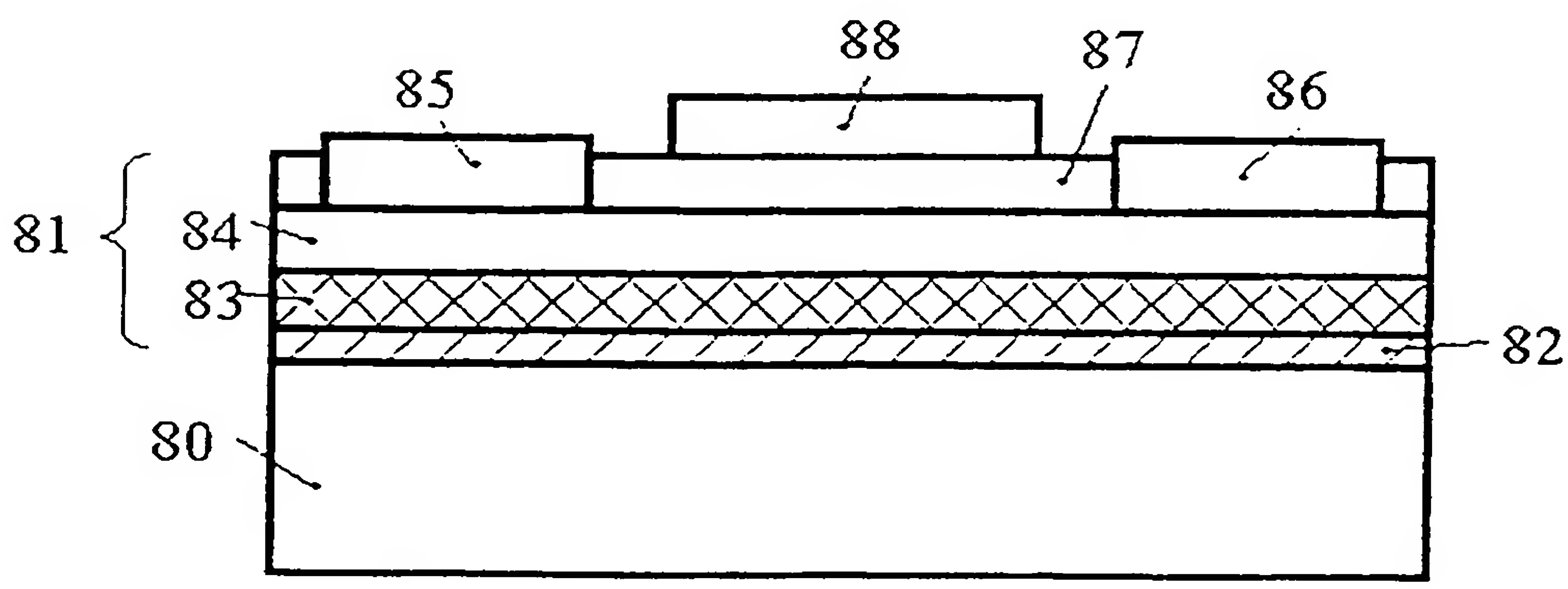

FIG.6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/RU98/00397

A. CLASSIFICATION OF SUBJECT MATTER H01L 33/00, H01S 3/19

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01S 3/18, 3/19, H01L 33/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched:

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No
A	EP 0678945 A1 (TOYODA GOSEI CO., LTD et al) 25.10.95	1 - 5
A	EP 0688070 A1 (TOYODA GOSEI CO., LTD et al) 20.12.95	1 - 5
A	US 5146465 A (APA OPTICS, INC.) Sep. 8, 1992	1 - 5
A	US 5321713 A (MUHAMMAD A. KHAN et al) Jun. 14, 1994	1 - 5
A	JP 09199419 a (NEC CORP) 31.07.97, abstract	1 - 5

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex

* Special categories of cited documents:

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"E" earlier document but published on or after the international filing date

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
23 February 1999 (23.02.99)	10 March 1999 (10.03.99)

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